Designing, Understanding, and Operating Complex Human-Machine Systems

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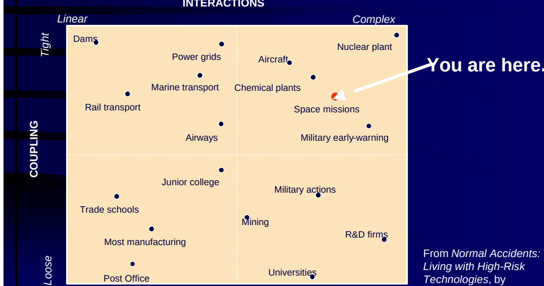
Portions of this work were performed by the Jet Propulsion Laboratory, California Institute of Technology under contract from the National Aeronautics and Space Administration.

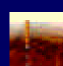
Risks from Complex Interactions & Tight Coupling



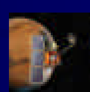
From *Normal Accidents: Living with High-Risk Technologies*, by Charles Perrow, 1984.

Challenges of Deep Space Missions

- Uncertain, hazardous environments
  - in situ science observations
  - need for autonomous operation
- Relatively long distances from Earth
  - long round-trip light-time delays
  - low data communication rates
  - infrequent communication



ballute



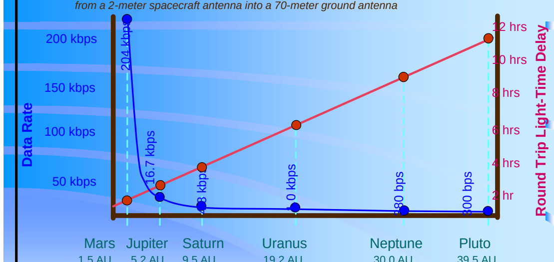
planetary orbiter

hydrobot in Europa ocean

Martian rover

Distance, Data Rate, Time Delay

Effect of distance on data rate for X-band RF communication with 5 watts transmitted power from a 2-meter spacecraft antenna into a 70-meter ground antenna



At orbit of Pluto it will take ~10 hours to send a command from Earth and receive acknowledgement!

AU = Astronomical Unit = mean Earth-Sun distance

Recent Disasters

- Clementine
  - error in low-level software wrote onto a memory-mapped I/O address that fired thrusters continuously, spacecraft spun out of control
- Ariane 5
  - software reused from Ariane 4 failed because larger numeric value exceeded range of its digital representation; inertial reference system shut down, launcher veered off course
- Mars Climate Orbiter
  - unit error in transferring navigation data, trajectory was too low, spacecraft burned up in atmosphere
- Mars Polar Lander
  - latent effect of an earlier spurious signal from a contact sensor prematurely aborted engine firing, spacecraft fell to surface

Motivating Examples

- Io Volcano Observer video
- Europa Cryobot video

Mars Robotic Outpost

Self-organizing societies of adapting exploration agents

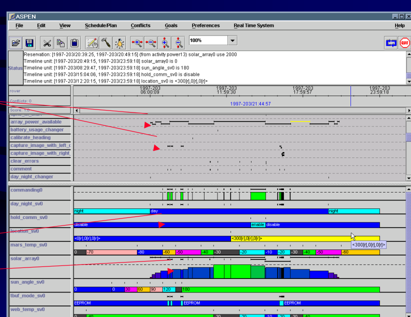
What is being done now?

- Uplink
  - Visualization of Plans/Schedules
- Downlink
  - Visualization of large correlated datasets of spacecraft telemetry

ASPEN Planner Displaying 1 Sol Rover Operations Plan

Planned Activities

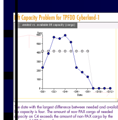
Affected States and Resources

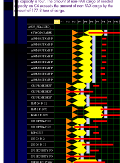


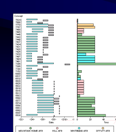
DITOPS-Visage

courtesy of

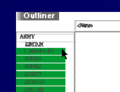
Robotics Institute, Carnegie Mellon University and MAYA Design Group



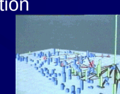




More traditional schedule displays
– activity & resource centered



But also animations and visualization of activities and data

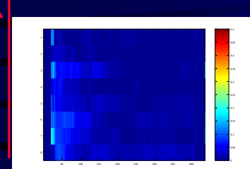


Issues

- How do we compute/visualize aggregate behavior?
  - What is the rover swarm doing?
  - Is the state of the subsystem OK, not is each individual sensor within nominal!
- How do we visualize flexibility and/or uncertainty?
- How do we represent a range of behaviors (discrete alternatives)?
- How do we visualize a region of the state space?
- How do we visualize bottlenecks?
- How do we visualize interactions?

Detection Results on Individual Signals

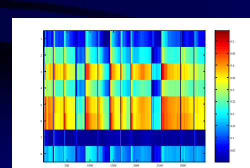
Channel Number (1 through 8)



- Test performed on F-15 Hydraulic System
  - "Iron Bird" flight hardware-in-loop test
  - Eight pressure sensors at 200 Hz
- Plot shows deviation of each signal measured at each sample
- Report is made at every sample regardless of confidence level

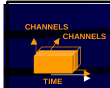
Nominal data result

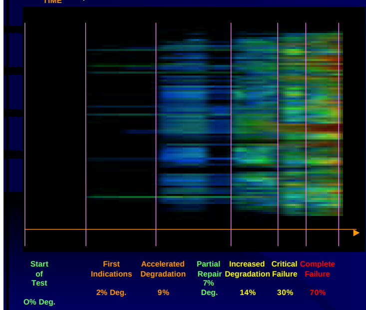
Time (Samples)



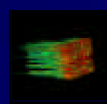
Anomalous Data result

Prognostic Assessment





- Simulation of complete aircraft hydraulic system over 25 flights
  - Model included 74 pressure sensors and actuator commands / position sensors
- Degradation changed on day-to-day basis
- Persistent deviation tracked



Conclusions

- Designing, Operating, Analyzing Complex Autonomous Systems is a growing challenge for space exploration systems
  - Future missions will have increased autonomy
  - Future Spacecraft will be more complex
  - Future missions will need to have more advanced techniques to visualize these behavior regimes in order to understand:
  - At design time that a design will perform properly?
  - During Operations to understand the spacecraft state and what the spacecraft has done?
  - During operations to understand what the spacecraft is doing and will do?